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Mapping the Cerrado's Vegetation Cover – A Review of Remote Sensing Initiatives

Mapeamento da Vegetação do Cerrado – Uma Revisão das Iniciativas de Sensoriamento Remoto

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Abstract: The Cerrado is the second largest Brazilian biome, being recognized as the most biodiverse savanna in the world. Beginning in 1970, the land use and land cover dynamics in the biome have been characterized by extensive agricultural activities, resulting in historically higher deforestation rates than the Amazon biome. This scenario reinforces the need to investigate the methodology initiatives of the Cerrado's vegetation cover, aiming to identify the gaps and challenges that still exist for the advancement of scientific knowledge in the Remote Sensing (RS) field. To this end, this review article identified 15 initiatives that mapped the biome's vegetation at different scales, periods, and legend levels. The first was the Radam/RadamBrasil project, in the 1970s. However, it was not until the 2000s that Cerrado began to have more visibility, with the emergence of larger and more targeted initiatives for the biome (PROBIO, Conservation International). Recently, new initiatives (MapBiomas, PRODES) have stood out for incorporating different methodologies that have followed the computational evolution of the Remote Sensing techniques. The research carried out in this article identified that the discrimination of different land cover types in the biome is still one of the main challenges to be overcome, especially regarding the non-forest phytophysiognomies as well as the land-use classes that are spectrally similar, such as pasture. This study aims to aggregate details of the main initiatives for mapping the Cerrado vegetation, as well as their methodologies, challenges encountered, such as the difficulty in discriminating its vegetation types, and further discussions and future prospects in the field of RS.
Keywords: Savanna. Phytophysiognomy. Orbital Sensors.

Resumo: O Cerrado é o segundo maior bioma brasileiro, sendo reconhecido como a savana mais biodiversa do mundo. Após 1970, as dinâmicas de uso e cobertura da terra do bioma têm sido marcadas por atividades agropecuárias extensivas, resultando em taxas de desmatamento historicamente superiores às do bioma Amazônia. Esse cenário reforça a necessidade de investigar a metodologia das iniciativas de mapeamento da vegetação do Cerrado, a fim de identificar as lacunas e desafios ainda existentes para o avanço científico do conhecimento no âmbito do Sensoriamento Remoto (SR). Para tal, o presente artigo de revisão identificou 15 iniciativas que mapearam a vegetação do bioma em diferentes escalas, períodos e níveis de detalhamento de legenda. O primeiro foi o projeto

Radam/RadamBrasil, ainda na década de 1970. No entanto, foi a partir dos anos 2000 que o Cerrado começou a ter mais visibilidade, com o surgimento de iniciativas maiores e mais direcionadas para o bioma (PROBIO, Conservação Internacional). Recentemente, novas iniciativas (MapBiomas, PRODES) têm se destacado por incorporarem metodologias diferenciadas que acompanharam a evolução computacional das técnicas de Sensoriamento Remoto. O levantamento realizado neste artigo identificou que a discriminação dos diferentes tipos de cobertura vegetal do bioma ainda é um dos principais desafios a serem vencidos, principalmente em relação às fitofisionomias não florestais, além de classes de uso espectralmente semelhantes, como a pastagem. Este trabalho visa agregar detalhes das principais iniciativas de mapeamento da vegetação do Cerrado, suas metodologias, desafios encontrados, tais como a dificuldade de discriminação de seus tipos de vegetação e maiores discussões e promessas futuras no campo do SR.
Palavras-chave: Savana. Fitofisionomia. Sensores orbitais.

1 INTRODUCTION

The Cerrado biome is one of the hotspots for global biodiversity conservation (MYERS et al., 2000) and is recognized as the richest savanna in terms of biodiversity, covering more than 10,000 plant species and exhibiting endemism rates of over 44% (SIMON et al., 2009). The biome stands out as the second largest in Brazil, occupying about 22% of the total area of the country and extending over two million km² (MMA, 2020a). It is also a significant carbon reservoir, with an estimated stock of approximately 8.73Gt of organic carbon, present in the biomass and soil compartment (REIS et al., 2017). Of a total of 12 hydrological regions present in Brazil, eight are located in the Cerrado, including the world's second-largest underground fresh water reserve, the Guarani Aquifer (REIS et al., 2017).

Despite its importance and associated risk, just 8.21% of the biome's territory is legally protected, and of this percentage, only 2.85% refers to Integral Protection Conservation Units. Among all the world's hotspots, the Cerrado is the one with the lowest proportion of fully protected areas (MMA, 2020a). The history of transformations that have occurred in the Cerrado has contributed to the emergence of highly impactful environmental damage, such as habitat fragmentation, extinction of biodiversity, exotic species invasion, soil erosion, pollution of aquifers, degradation of ecosystems, alterations in wildfire patterns and imbalances in the carbon cycle.

After 1970, occupation in the biome intensified, mainly due to the production of grains such as soybeans, corn and beans, although cultivated pastures are one of the most common types of use and occupation (SANO et al., 2010). Deforestation rates in the Cerrado have historically been higher than in the Amazon rainforest due to the lower level of government effort put towards its conservation (KLINK; MACHADO, 2005; SANO et al., 2019b). Machado et al. (2004) estimated deforestation rates of 1.5% and 0.67% per year in the 1985-1993 and 1993-2002 periods, respectively; these periods correspond to the increase of cattle raising and, later, to the intensification of soybean planting. For the period 2002-2013, TerraClass Cerrado shows that the biome lost its natural vegetation at a rate of 0.41% per year, much higher than the rate of 0.29% in the Legal Amazon over the same period (SANO et al., 2019b). Projections for 2050 indicate that the Cerrado may lose up to 34% of its native vegetation, leading to the extinction of at least a thousand endemic species, which would correspond to an impact eight times greater than all plant extinction worldwide since the year 1500 (STRASSBURG et al., 2017).

Evidence of the Cerrado's formation, along with climatic, geological, soil and land management conditions over the years have created phytogeographic conditions that have allowed for the highly heterogeneous forest, savanna and grassland formations present in the biome. From a physiognomic perspective, the forests are characterized by the predominance of arboreal species, where there is continuous or discontinuous canopy formation. The term savanna refers to shrubs and trees scattered throughout a grassy stratum, without continuous canopy formation. Finally, grasslands are areas with predominantly herbaceous and some shrubby species, with no trees in the landscape (RIBEIRO; WALTER, 1998; WALTER, 2006; GIROLAMO NETO, 2018). These formations were divided into fourteen phytophysiognomies according to the Brazilian vegetation technical manual and, therefore, require different management techniques and exploitation/preservation levels in each one of them.

To understand the transformations that have occurred in the biome and the future of the remaining natural vegetation, it is necessary to go back in time and analyze the vegetation mapping initiatives, the gaps between them and the evolution of the environmental discussion about the biome. In this sense, Remote Sensing emerges as a powerful tool for mapping vegetation and the temporal dynamics of suppression versus agricultural expansion in the biome. A major challenge in this context is the mapping of the various physiognomies, given the gradual disfigurement of these environments caused by degradation and anthropization, increasing in spectral confusion between classes. For example, the Cerrado lost 106,427 km² of its area between 2002-2011, with an average loss of ~0.7% of biome area per year (MMA, 2015a). If this rate of loss continues, the challenge of monitoring and mapping vegetation will increase in the future, along with the need for control and enforcement of agricultural expansion in the Cerrado.

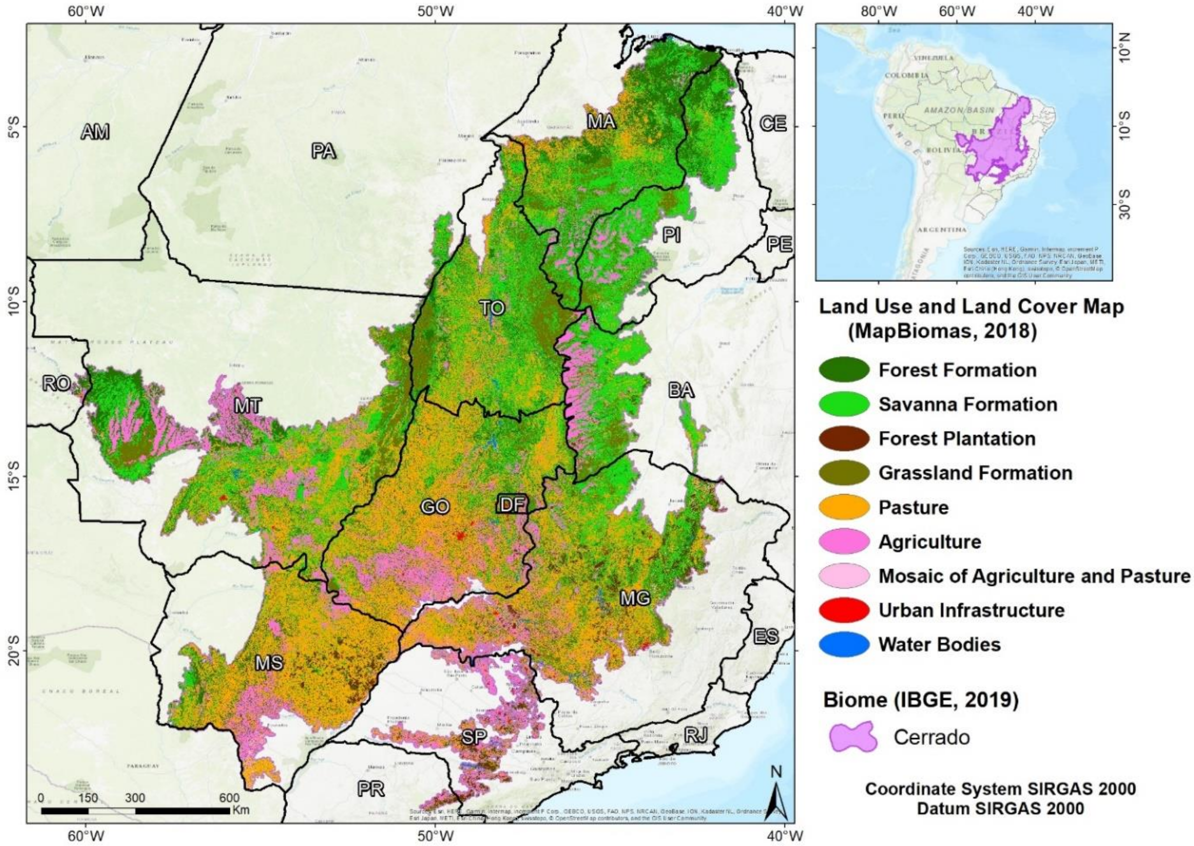
Among these initiatives, the vast majority use optical sensors of medium to moderate spatial resolution (30-250 m). Recent research indicates that high spatial resolution sensors are essential to discriminate larger hierarchical levels in the classification of multiple plant physiognomies (GIROLAMO NETO; FONSECA; KÖRTING, 2017; NEVES et al., 2020). In addition, object-oriented techniques such as GEOBIA have proven useful to perform pixel segmentation in homogeneous regions before performing the classification itself, bearing in mind that this technique reduces the classification error in a heterogeneously complex environment (NEVES et al., 2020). Deep learning machine classifiers, a technique known as Deep Learning, will be the future of pattern recognition in images, as they allow for contextual information to be involved in the analysis, achieving accuracy that is often greater than 90% in classification. The advance of cloud computing, especially when used in tandem with multiple data/sensors (optical, radar, LiDAR, climatological, etc.), also paves the way for new techniques and methods of image processing at multiple scales, allowing for a better understanding and evaluation of classes and their transitions.

In this context, this study aims to aggregate details of the main Cerrado vegetation mapping initiatives, their methodologies, challenges encountered, such as the difficulty of discriminating their vegetation types, and also present greater discussions and prospects within Remote Sensing. Thus, this work is divided into three parts: in the first part, we bring the definition of the Cerrado and its main subdivisions (phytophysiognomies), which are useful to guide the initiatives of mapping the biome. In the second part, we present the main regional and continental initiatives for mapping the Cerrado vegetation, with public data made available to the community. Finally, in the third part, we establish guidelines and future perspectives for mapping the Cerrado, whether at local or regional levels, to increase the accuracy of classification, as well as to provide more detailed hierarchical levels of the main physiognomies.

2 THE CERRADO

The Cerrado biome is present in the states of Goiás (GO), Tocantins (TO), Mato Grosso (MT), Mato Grosso do Sul (MS), Minas Gerais (MG), Bahia (BA), Maranhão (MA), Piauí (PI), Rondônia (RO), Paraná (PR), São Paulo (SP) and Distrito Federal (DF) (Figure 1).

Figure 1 - Cerrado Biome: land use and land cover of the main natural and anthropic classes.



Source: The authors (2020).

The climate of the Cerrado is characterized as seasonal, alternating between a cold and dry winter (from April to September) and a hot and rainy summer (from October to March), with relative humidity reaching critical levels in the winter (MIRANDA; SILVA; MIRANDA, 1996). The average annual precipitation is 1,500 mm, and the temperatures are generally mild throughout the year, varying between 22ºC and 27ºC on average (KLINK; MACHADO, 2005). Due to climatic conditions and water availability, the presence of fire is constant during the dry season, and is considered a determining factor in the modification of the biome landscape (ARMANDO, 1994). Fire is an ancient and widely used management tool in the handling and conservation of tropical landscapes and, although the Cerrado is an ecosystem adapted to natural fire, the fires used to stimulate the re-growth of pastures and expand agricultural frontiers cause problems such as loss of biodiversity, alterations in the structure of ecosystems, and loss of nutrients, among others (MISTRY; BIZERRIL, 2011).

The Cerrado vegetation has several phytophysiognomies that, according to Ribeiro and Walter (1998), are divided into forest formations (Ciliar Forest, Gallery Forest, Dry Forest and Cerradão) (Figure 2), savannas formations (Cerrado restricted sense, Cerrado Park, Palmeiral and Vereda), and grasslands formations (locally called Campo Sujo, Campo Rupestre and Campo Limpo) (Figure 3). The criteria adopted for the differentiation of these classes are based, firstly, on their form, which is defined by the structure, dominant growth modes and possible seasonal changes. Subsequently, soil and floristic composition factors are considered. In the case of phytophysiognomies characterized by subtypes, the environment and floristic composition were the differentiation criteria used by the authors. These formations have different origins, classifications and phytophysiognomies.

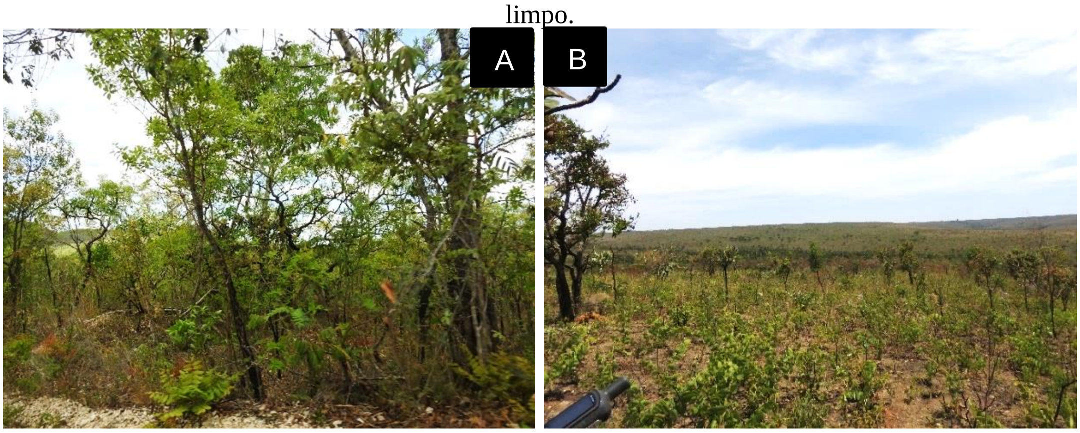
The Cerrado forest formations are the result of substantial changes in climate and geomorphology, which led to the expansion and retraction of the Amazon and Atlantic forests, as well as the semideciduous Caatinga forests. In quaternary glacial periods, which were typically dry, dry forests, and open vegetation formations expanded, reaching areas that today belong to the Cerrado (RIBEIRO; WALTER, 1998). Evidence of this nature is characterized by the geographical distribution of many native species of these forests in different biomes or disjointed areas that include the Cerrado (BIGARELLA; ANDRADE-LIMA; RIEHS, 1975). At the same time, from a spatial perspective, formations such as these would be influenced by local variations in hydrography, topography, and soil and aquifer depth.

Figure 2 - Field photos of two national parks - the National Park of Brasília (DF) and of Chapada dos Veadeiros (GO). a) forest formation: ciliar forest; and b) Cerradão.

Source: The authors (2020).

The origin of savanna and grassland formations, in turn, is widely discussed in the literature related to the subject (BEARD, 1953; ALVIM, 1954; EITEN, 1972; COUTINHO, 1978; GOODLAND; FERRI, 1979). According to Eiten (1994), physiognomic forms of the Cerrado would depend on the fertility, the soil depth and its degree of water saturation. Rainfall, on an evolutionary scale, has weathered soils, reducing the content of essential nutrients and increasing the availability of aluminum. Hence, it can be said that vegetation was defined as an indirect result of the climate. Ribeiro and Walter (1998) synthesized the various existing theories to explain the emergence of these formations in three groups, using terms suggested by Beard (1953): 1 – vegetation would be the result of climate, mainly due to seasonal water limitation in the dry season (climatic theories); 2 - vegetation would be the result of anthropic action, mainly due to the frequent use of fire; or still resulting from the activity of other biological agents, such as ants (biotic theories); and 3 - vegetation would be dependent on soil and geological aspects, such as the absence of minerals, aluminum excess, drainage difference and soil depth (pedological theories).

Figure 3 - Field photos of two national parks - the National Park of Brasília (DF) and of Chapada dos Veadeiros (GO). a) savanna formation: cerrado restricted sense; and b) grassland formation: campo sujo and, to the horizon, campo limpo.



Source: The authors (2020).

The main cause of Cerrado vegetation suppression is agricultural expansion, mainly due to meat and grain production in Brazil. Control of deforestation in the Amazon, which intensified beginning in 2004 with the Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), changed this agricultural frontier for places where there is less rigidity in terms of compliance with the law (leakage). The suppression of vegetation is permitted by law in up to 65% of the area, as opposed to 20% in the Amazon (BRASIL, 2012). In 2006, the soybean moratorium was implemented in the Amazon, with the commitment of not commercializing the production of grains from deforested areas after the implementation of the agreement

(GIBBS et al., 2015; FARIA, 2018). Later, in 2008, the list of priority municipalities in the Legal Amazon was created as a restrictive measure, in which participating municipalities would suffer sanctions. The Cerrado, which at the time was protected only by the existing forest code, began to be exploited in its natural remnants, mainly in the MATOPIBA region (Maranhão, Tocantins, Piauí and Bahia States). In addition to having the largest remnants of the biome, this region has a much lower land value than the already consolidated regions (FARIA, 2018).

MATOPIBA is currently considered the new agricultural frontier of the country because it has a flat topography, deep soils and a favorable climate for the cultivation of the main grain and fiber crops. The MATOPIBA region is made up of 337 municipalities and represents about 73 million hectares, of which 61.20% is composed of savanna coverage which, in turn, has the largest number of endemic species (WALTER, 2006). There are also 324,000 agricultural establishments, 46 conservation units, 35 indigenous lands and 781 agrarian reform settlements in the region, according to a survey made by the Strategic Intelligence Group (GITE) of Embrapa (EMBRAPA, 2019). This scenario reinforces the importance of fighting deforestation in the biome, especially in strategic areas, avoiding the vegetation fragmentation and the increase of isolated spots.

3 INITIATIVES FOR VEGETATION MAPPING

Within the scope of Remote Sensing, the **Radam Project (1970)** is considered the first national mapping for knowledge and appropriation of the country's natural resources. Its objective was to survey the natural resources in a portion of the Amazon through Radar Remote Sensing (SLAR - Side Looking Airborne Radar) (IBGE, 2018). After the mapping' success, it was expanded to the entire national territory and renamed **RadamBrasil (1975)**. Both projects used the Sud SE.210 Caravelle airplane (IBGE, 2018), flying at an average altitude of 12 km and an average speed of 690 km/h. The sensor system coupled to the aircraft was the GEMS (Goodyear Mapping System 1000), operating in the X band (wavelengths close to 3 cm and frequency between 8 and 12.5 GHz) (ESCOBAR et al., 2005).

As a result, for ten years and relying on about 700 professionals, the project produced 38 volumes of the "Natural Resources Survey Series", which contained reports and thematic maps in 1:1,000,000 scales and image-charts in 1:250,000 with geological, geomorphological, pedological, potential land use and vegetation surveys (IBGE, 2018). In terms of vegetation, some image-charts cover the Cerrado vegetation, such as in Goiás, Goiânia, and Brasília States, among others. In addition to the GEMS system, this mapping also used MSS/Landsat 2 sensor images, visual interpretation, and a series of field visits to analyze vegetation at the physiognomic level. All this material is available in the IBGE online library (IBGE, 2020).

Since 1982, working for the RadamBrasil Project, Góes Filho and Veloso (1982) have proposed a new physiognomic-ecological system for the classification of Brazilian vegetation (Figure 4), with the addition of a legend for regional-scale mapping. This work also served as a basis for the classification of Brazilian vegetation (VELOSO; RANGEL FILHO; LIMA, 1991) and for the elaboration of the technical manual of Brazilian vegetation (IBGE, 1992), both of which are from the Brazilian Institute of Geography and Statistics (IBGE) and have been updated over the years. Finally, the RadamBrasil project broadened the focus to geosciences in Brazil, promoting varied research that began to highlight the potential of Remote Sensing in environmental studies.

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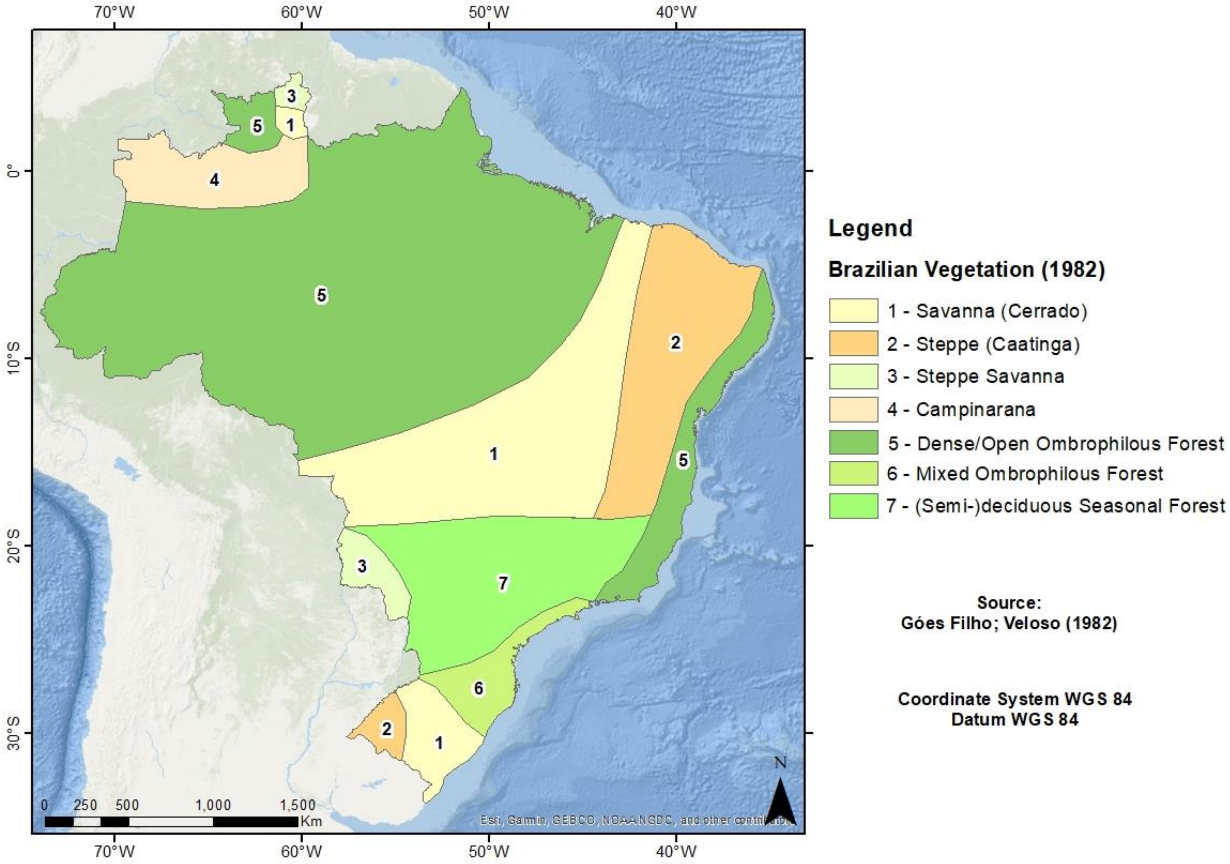
Figure 4 - Schematic map of Brazilian vegetation (1982).

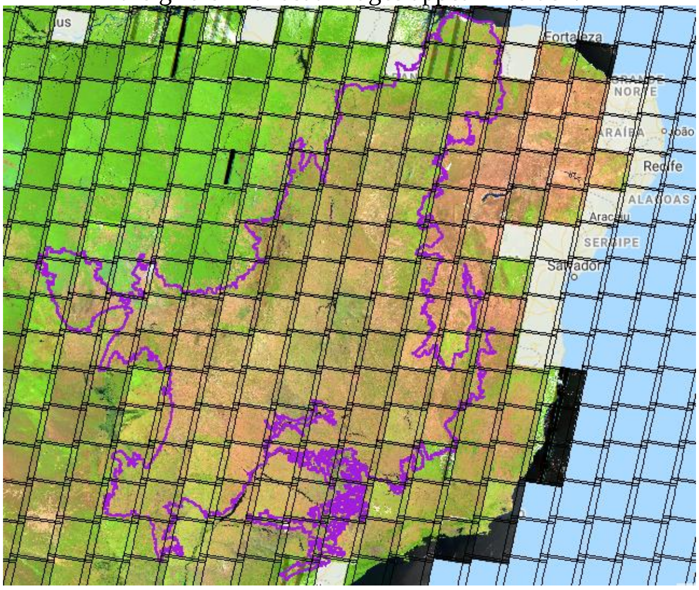


Source: The authors (2020), adapted from GÓES FILHO; VELOSO (1982).

Despite its successful record, RadamBrasil was discontinued in 1985, causing new initiatives to emerge to fill the data gap, especially in the late 1980s. As a result, **PRODES (1988)** was created, motivated by two previous studies that demonstrated the potential of using orbital data from the Landsat system to evaluate the impact of the implementation of agricultural projects in the Amazon (TARDIN; SANTOS; NOVO, 1977) and to survey deforested areas in the Brazilian Legal Amazon (TARDIN et al., 1979). However, PRODES was limited only to the Amazon region, covering a negligible portion of savanna phytophysiognomies in the Cerrado, restricted to the Brazilian Legal Amazon and in transition zones.

The estimated conversion of vegetation remaining in the Cerrado between 1970-2000 is inaccurate, mainly because of RadamBrasil data's reliance data as a basis for further studies (FARIA, 2018). However, the mapping of the biome began to gain greater visibility in the 2000s, when the Ministry of the Environment (MMA) published two edicts for the selection of subprojects for mapping vegetation cover through the Project for the Conservation and Sustainable Use of Brazilian Biological Diversity, **PROBIO (2004)**. The PROBIO subprojects used ETM+/Landsat 7 images from 2002 covering all biomes on a scale of 1:250,000 (MMA, 2009). For the Cerrado, the study was a cooperation between Embrapa Cerrados, the Federal University of Uberlândia (UFU) and the Institute of Socio-Environmental Studies at the Federal University of Goiás (IESA/UFG), and these data are available on the MMA website (MMA, 2020).

Figure 5 - ETM+/Landsat 7 surface reflectance images from 2001-2003, in R5G4B3 composition and filtered for less than 30% clouds, illustrate PROBIO initiative (2004). The central purple limits refer to the Cerrado biome’s limits and the grid of Landsat images appear in black.



Source: The authors (2020).

In the PROBIO framework, the biome was mostly analyzed from a mosaic of 114 ETM+/Landsat 7 images (illustration in Figure 5) corresponding from August to October, coinciding with the dry season and lower cloud cover (MMA, 2007). The project methodology differs from other initiatives by using image segmentation techniques, reducing visual interpretation time. When considering 2002 as the base year of the study, the results obtained by PROBIO indicated that native vegetation represented 60.42% of the biome; however, this percentage considers approximately 28 million hectares of pasturelands as native vegetation (computed by the 1995/1996 IBGE Agricultural Census). When considering this value as anthropic, the remaining native vegetation was reduced to 46.74% (SANO et al., 2007). Furthermore, the results indicate (Table 1) that most of the vegetation remaining in the biome in 2002 was composed of savanna formation physiognomies (36.73%), while in the anthropized área, the cultivated pastures (26.45%) covered a larger portion of the biome (MMA, 2007). It is important to point out that these results refer to the old limits of the biome, proposed by IBGE, which were updated in 2019. Thus, the comparison of the percentage of PROBIO results with current results may not be compatible.

Table 1 – Area occupied by natural vegetation cover in each state covered by the Cerrado vegetation. *The Rondônia portion of the Cerrado was not listed in the results due to its being very small, however, this portion was included in the value for Mato Grosso (MT).

State*	% of biome in the state	Forest Formation (ha)	Savanna Formation (ha)	Grassland Formation (ha)	Natural Vegetation (%)
SP	33	833,387	210,441	34,888	**13**
PR	2	20,558	14,048	84,085	**32**
MS	61	2,867,267	3,599,826	468,311	**32**
DF	100	44,645	162,718	6,164	**37**
GO	97	2,929,033	11,090,161	687,502	**44**
MG	57	3,279,762	11,322,147	3,192,964	**53**
MT	40	7,717,102	15,868,080	155,151	**66**
BA	27	3,333,902	7,357,605	518,389	**74**
TO	92	4,639,932	13,362,688	2,249,165	**79**
MA	65	12,337,965	6,032,951	382,790	**89**
PI	37	2,319,035	6,210,085	61,462	**91**

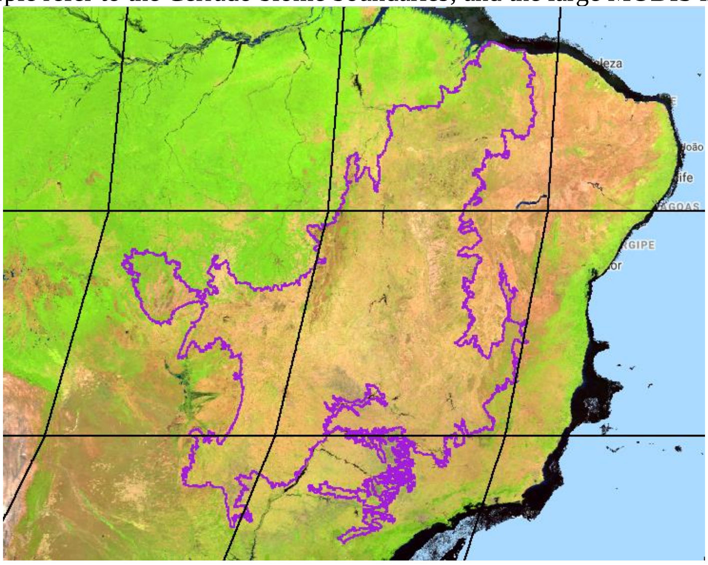
Source: Adapted from MMA (2007).

The overall accuracy and Kappa index for the PROBIO mapping results were 74.19% and 68.31%, respectively. The greatest discrepancies were observed between the cultivated pasture classes and the agricultural crop and reforestation classes, which can be explained by the greater spectral similarity between them. According to the authors, intra-class confusion can also be the practice of crop rotation in the same area, in addition to reforestation projects in early stages. By grouping the classes in a more comprehensive legend level (natural, anthropic, and water mass coverage), the rates have increased to 96.5% and 92.3%.

The Brazilian organization **Conservation International (2004)** (MACHADO et al., 2004) conducted a mapping of the Cerrado using the MODIS sensor product MOD43b4 (at the time, a relative of NBAR - Nadir BRDF-Adjusted Reflectance). This data was chosen because of its greater stability and consistency, and because it is a product adjusted for the removal of angular effects. Thus, the initiative used nine images from 2002 (illustration in Figure 6), classified by the supervised method for maximum likelihood (MaxVer) and validated by visual interpretation from ETM+/Landsat 7 scenes. The result indicated that 54.9% of the Cerrado corresponded to native areas deforested in that year (MACHADO et al., 2004).

However, the authors themselves claimed that the results were overestimated due to the spatial resolution of the data used (1 km) combined with the absence of field visits to validate the data. Even so, the initiative represented a major contribution to studies aimed at quantifying the Cerrado vegetation, as it clarified that, although the remnants were associated with extensive areas in numerical terms, these plots were largely in areas of land unfavorable to the implementation of large agricultural projects or lacking basic infrastructure. Machado et al. (2004) still estimated deforestation rates of 1.5% and 0.67% per year (approximately 30,000 km² and 22,000 km² per year) for the 1985-1993 and 1993-2002 periods, respectively, periods that were related to increased cattle raising and, later, to the intensification of soybean plantations. Finally, the authors estimated that the Cerrado would disappear in 2030 if deforestation rates were maintained at the same frequency and intensity.

Figure 6 – MODIS NBAR images from August/2002, R6G2B1 composition, illustrate the Machado et al. (2004) initiative. The limits in purple refer to the Cerrado biome boundaries, and the large MODIS image tiles appear in black.



Source: The authors (2020).

Also, in 2004, **Eva et al. (2004)** produced a ground cover map of South America, using 1995-2000 images from ATSR-2 (Along Track Scanning Radiometer), SPOT VGT and DMSP OLS (Defense Meteorological Satellite Program - Operational Linescan System), all with a 1 km spatial resolution. The Cerrado is represented in the mapping by the grassland, savanna, and agriculture classes. However, as it is a map of greater geographical coverage, the level of detail for vegetation classes is more generalized.

The gaps in mapping the Cerrado in the following years were partially filled by some state initiatives, such as those of **São Paulo (2005)** and **Minas Gerais (2006)**. The São Paulo State Forest Institute carried out the spatial characterization and quantification of natural remnants and reforestation with exotic species (Pinus and Eucalyptus) in the state. For this, the initiative made use of CBERS-2 images from 2000-2001, photointerpretation with TM/Landsat 5, ETM+/Landsat 7 images, and aerial photographs. In the end, 3.5 million hectares (14% of the state) of the area were mapped, among which 210,000 hectares (0.85% of the state) correspond to Cerrado phytophysiognomies (KRONKA et al., 2005; SANO et al., 2007). In the following years, Scolforo and Carvalho (2006) published a book through the University of Lavras on the mapping and inventory of native flora and reforestation in the state of Minas Gerais. The authors used TM/Landsat 5 and ETM+/Landsat 7 images from 2003 (spring, summer, and winter), field data, Tasseled Cap transformation and

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decision trees classification. The results were 90.8% accurate for a legend level specific to Cerrado phytophysiomies (CARVALHO, 2005).

In 2008, the MMA, together with the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) and the United Nations Development Program (UNDP), initiated the Project for Monitoring the Deforestation of Brazilian Biomes by Satellite (PMDBBS). The main goal of **PMDBBS (2008)** was to combat illegal deforestation in non-amazon biomes (Cerrado, Caatinga, Atlantic Forest, Pampa and Pantanal), based on surveys conducted by PROBIO, but on a more refined scale of 1:50,000 (MMA, 2009). To this end, the project quantified deforestation in areas of native vegetation to subsidize the definition of priority enforcement actions (MAURANO; ALMEIDA; MEIRA, 2019). The data can be accessed on the MMA website (MMA, 2020).

The mapping of the areas deforested in the Cerrado by PMDBBS used TM/Landsat 5 and CBERS2B images during the period 2002-2011, with polygons of at least two hectares, interpreted by visual detection and manual digitalization of the remaining vegetation areas identified by PROBIO. The polygons with deforestation detected were considered as anthropized areas, with no other classes identified. In addition to the period analyzed (2002-2011), the project also reviewed the PROBIO polygons (deforestation occurred until 2002), which resulted in the rectification of the deforested area of the biome from 38.98% to 43.67% (MMA, 2009). This percentage was increased to 48.89% in 2011 of total deforested area, with an accuracy of 88% (Table 2), when the initiative was discontinued. The project also pointed to an annual deforestation rate for the period 2002-2008 of 0.69% in the Cerrado, the highest rate observed in comparison to other Brazilian biomes (Pantanal: 0.47%, Amazon: 0.42%, Caatinga: 0.33% and Pampa: 0.20%) (MMA, 2009).

Table 2 – Total Cerrado area deforested by period, from 2002 to 2011.

	Area deforested (km²)					Total area deforested	
Biome (km²)	Prior to 2002	2002-2008	2008-2009	2009-2010	2010-2011	km²	**%**
2,039,386	890,636	85,074	7,637	6,469	7,247	997,063	**48.89**

Source: Adapted from MMA (2015b).

The MMA, together with LAPIG (Laboratory of Image Processing and Geoprocessing) and the NGOs The Nature Conservancy and Conservation International, initiated the initiative SIAD (Deforestation Alert System). **SIAD (2008)** used MODIS vegetation index data to estimate changes in the vegetation cover of the biome’s remnants in 2002-2009 (MMA, 2009). The data obtained were made available for public access on the initiative's interactive online platform, and the publications linked to the project can be accessed on the LAPIG website (LAPIG, 2020).

The Cerrado Land Use and Land Cover Mapping Project **- TerraClass Cerrado (2013)** is the result of a partnership between MMA, IBAMA, INPE, EMBRAPA, UFG and UFU, and its results are available on the INPE website (INPE, 2020). The initiative provided more robust results of land use and land cover in the Cerrado, refining the classes from 121 OLI/Landsat 8 images for the year 2013 (MMA, 2015a). After segmentation, the segments were exported with the SPRING classification module, and each class was defined individually based on specific parameters such as the use of agricultural masks, vegetation index (NDVI), and filtering, among others (MMA, 2015a).

According to the latest TerraClass Cerrado results (Table 3), the total area mapped in the biome was 2,039,243 km², with 1,111,090 km² (~ 54%) corresponding to natural vegetation categories (forests, savannas and grasslands). The initiative obtained 80.2% accuracy in its mapping, which is considered a high and acceptable value, especially given the level of detail in the legend. A criticism of this data is about the confusion between classes. For example, the class "Pasture" refers only to cultivated pastures, disregarding native pastures, where there is also land use, but the vegetation is natural. These, in turn, were classified as natural non-forest areas (SANO et al., 2019b). Even so, the transformation of native vegetation areas into pasture and agriculture is notorious and directly proportional, so much so that agriculture/livestock has become the greatest threat to the Cerrado. The project also showed that in the period 2002-2013, the rate of loss of natural vegetation in the biome was 0.41% per year, considerably exceeding the rate of 0.29% in the Legal Amazon for the same period (SANO et al., 2019b).

Table 3 – Results from TerraClass Cerrado (2013). The minimum mappable area is 6.25 hectares and the compatible cartographic scale is 1:250,000.

Classes	Area (km²)	Area (%)
Natural		
Natural Forest	418,789	20.54
Natural Non-Forest (Savanna and Grassland)	692,301	33.95
Natural non-vegetative (sandbanks, outcropping)	2,609	0.13
Water	15,056	0.74
Anthropogenic		
Annual Agriculture	174,006	8.53
Perennial Agriculture	64,512	3.16
Mining	247	0.01
Mosaic of occupations	2,326	0.11
Pasture	600,832	29.46
Silviculture	30,525	1.50
Exposed soil	3,621	0.18
Urban	8,797	0.43
Others	73	0.00
Non-observed (burned, clouds)	25,549	1.25
Total	**2,039,243**	**100**

Source: Adapted from INPE (2019a).

One of the most important works in the literature related to this theme is the **Global Forest Change (2013)**, proposed by Hansen et al. (2013), which mapped the gain and loss of global forest from 2000 to 2012. Although this is a mapping effort globally, the surveys were conducted with ETM+/Landsat 7 (30 m) orbital images, which allows for a medium resolution visualization for the proposed scale. Brazil stands out in this study for having reduced deforestation rates for the period mentioned above. Also, the authors also drew attention to the fact that the country is the only one that produces and maintains the transparency of annual data on forest extent and changes in land use and coverage. The global data set for this project is divided into 10x10 degree images, consisting of files that include, among others, forest gain and loss data with 99.6% accuracy. The data were generated by automated classifications based on decision tree algorithms and are available on the platform created by Hansen et al. (2013).

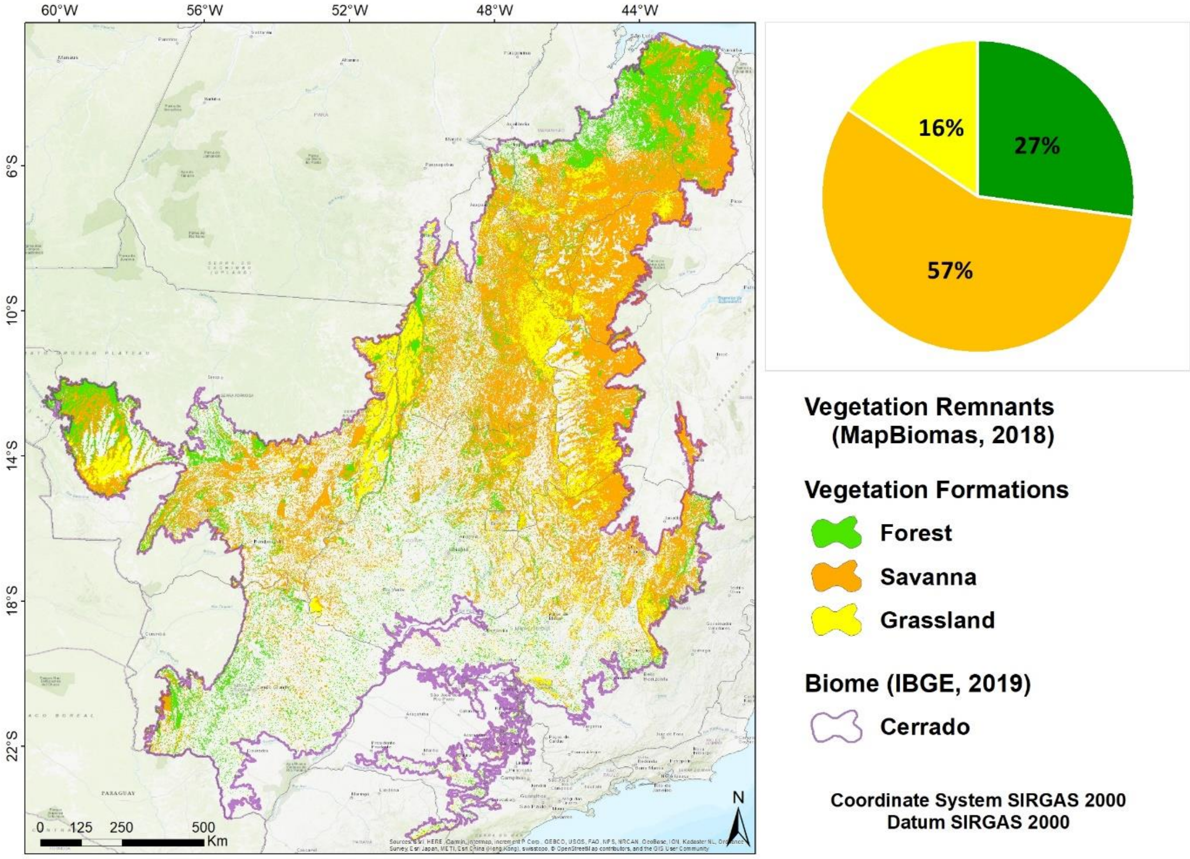
Considering that the Cerrado is proportionally less studied in comparison to the Amazon, and given the even greater lack in the scientific literature of studies aimed at mapping the vegetation of the Caatinga biome, **Beuchle et al. (2015)** produced consistent data on land cover changes in both biomes between 1990 and 2010. Using TM/ETM+/Landsat images and object-oriented classification, the authors concluded that the Cerrado vegetation remnants represented less than half of the total area of the biome in 2010 or 47%.

In 2015 came the High-Resolution Mapping of Brazilian Biomes Project, created by the Brazilian Foundation for Sustainable Development **- FBDS (2015)**, a non-profit organization whose projects have as one of their focuses the sustainable development of rural areas. This approach led to the emergence of mapping biomes by satellite images, which had as its main objective the production of primary data on land use and coverage, hydrography, and Permanent Preservation Areas (PPA). One of the innovative aspects of this project was the adoption of an unprecedented scale (1:25,000), in addition to the use of data from the RapidEye satellite (5 meters) (FBDS, 2015). The mapping was generated to 2013 year and used the visible and near infrared bands for each image. The images were classified by the supervised method to be then vectorized. The initiative obtained 95% accuracy highlighting the potential of high-resolution images to help discriminate between classes, despite the more specialized level of legends compared to other initiatives. Data from this mapping are available for the Cerrado and Atlantic Forest biomes, and can be accessed at the FBDS website (FBDS, 2015).

In the same year, experts from different areas met in a seminar to discuss new opportunities for mapping the national territory in the scope of remote sensing, which gave rise to the Annual Mapping Project of Land Cover and Land Use in Brazil **- MapBiomas (2015)**. This multi-institutional initiative produces data from 1985 to the present day through the cloud processing platform Google Earth Engine (GEE), totaling over 30 years of mapping for the six Brazilian biomes. The initiative uses TM/Landsat 5, ETM+/Landsat 7, and OLI/Landsat 8 images and a series of metrics for each biome and cross-cutting themes to generate a single mosaic for the entire country (MAPBIOMAS, 2020a).

This mosaic is saved as data collection (Asset) in the GEE, and the biome and cross-theme groups generate mapping layers using the Random Forest classification algorithm automatically. These layers are then integrated and a single final map is generated (MAPBIOMAS, 2020a). It is not necessary to understand Javascript or programming notions to access the data because, in addition to an interactive platform, MapBiomas has produced a toolkit with tutorials to access the data on its website (MAPBIOMAS, 2020). According to the MapBiomas 5.0 collection (Figure 7), the natural remnants of the Cerrado biome's forest, savanna and grassland formations account for 27%, 57%, and 16%, respectively, of a total of 1,065,283 km² in 2018, which represents less than half of the biome's total area.

Figure 7 - Remaining natural Cerrado biome vegetation in 2018 from the MapBiomas 5.0 collection data.



Source: The authors (2020).

The global accuracy associated with MapBiomas project maps has consistently evolved, increasing from 79% in collection 2 to 91% in collection 5, launched in August 2020. In this collection, the statistics provided so far have not been considered last year (2019), and for level I classification, the maps corresponding to the Cerrado biome offer accuracy of 83.8%. The main source of error in the classifications provided is linked to the class "Non-Forestry Natural Formation", which is 51% of the evaluated samples was erroneously classified as "Agriculture/Livestock" or "Forest" (inclusion error). Likewise, 45% of the samples classified as non-forest formations corresponded, in the validation sample, to another type of coverage (forest or agricultural) (omission error). As expected, the accuracy corresponding to level II classification is lower. The overall accuracy at this classification level is 81.6%, with the greatest intraclass discrepancy being related to the "Grassland Formation" class, which registers inclusion and omission errors of 51.5% and 44%, respectively, for the year 2018.

The accuracy corresponding to the Cerrado biome is relatively low compared to the overall accuracy of the Amazon biome (97.6%) and the overall accuracy of all grouped biomes (91.2%). It is understood that this is mainly due to two factors: 1) the already mentioned complexity involved with discriminating between the types of natural non-forest vegetation of the Cerrado and 2) the difference in the methodologies used by the MapBiomas project for the Amazon and the Cerrado. Indeed, the team in charge of the Amazon biome used, in the classification algorithm, the entire set of Landsat images recorded for the biome, from 1985 to 2018. The other biomes were classified using a single representative image for each year, incorporating up to 105 metrics corresponding to the annual time series, such as the average, maximum, and minimum value of each band and various indexes and spectral fractions. It is expected that the homogenization of the algorithmic treatment of the different biomes will bring an expressive increase in the accuracy of the classifications corresponding to the Cerrado biome in the next collections of the MapBiomas project.

Starting in 2016, INPE developed **PRODES Cerrado (2016)** through the Brazilian Biomes Environmental Monitoring Program, thus starting the mapping of deforestation throughout the biome. The project produced a biennial historical series for the period 2000-2012 and an annual historical series for the period 2013-2017 and, particularly in 2016 and 2017, the data produced come from the FIP FM Cerrado project (MAURANO; ALMEIDA; MEIRA, 2019). Following the PRODES methodology, the images used come from the Landsat constellation (TM/Landsat 5 and OLI/Landsat 8) on a cartographic scale of 1:250,000 and a methodology based on photointerpretation, through the TerraAmazon system.

First, the project selected images from the year 2000 to create a mask of existing deforestation. For subsequent years, increments of deforestation were identified based on a cumulative approach, i.e., ensuring that old deforestations are not mapped again (MAURANO; ALMEIDA; MEIRA, 2019). The quantification occurs in areas with suppression greater than one hectare, and the occurrence of deforestation is considered only when there is a complete removal of native vegetation. This approach guarantees the inclusion of all the biome's phytophysiognomies and all data can be accessed on the Terra Brasilis platform (TERRABRASILIS, 2020). According to data from PRODES Cerrado, deforestation in the biome reached 283,200 km² between the years 2001 and 2019, with more than 28,000 km² correspondings to areas less than 6.25 ha (INPE, 2020c). In this period, the most deforested states were Mato Grosso (46,054 km²), Goiás (45,137 km²) and Minas Gerais (44,823 km²).

In addition to the mapping explicity aimed at generating deforestation and land use and cover data, the **DETER-B (2018)** system deserves to be highlighted for having included the Cerrado biome in the deforestation warnings and alerts as of 2018 (INPE, 2020d). The initiative identifies and maps, almost in real-time, deforestation and forest cover changes with a minimum area close to one hectare, using CBERS-4, IRS (Indian Remote Sensing) images, and visual interpretation, along with the Linear Spectral Mixing Model (LSMM) technique (INPE, 2020e). These alerts are sent directly to IBAMA, which then proceeds with the surveillance protocols for these areas. These data are available on the TerraBrasilis platform, together with the PRODES data. Table 4 presents a summary of the 15 Cerrado mapping initiatives described in the previous paragraphs.

Table 4 - Summary of Cerrado vegetation mapping initiatives.

Initiative	Objective	Sensor	Accuracy/Kappa
1975/RadamBrasil	Thematic reports and maps in scales 1:1,000,000 and image-charts in 1:250,000 with surveys using geological, geomorphological, pedological, potential land use and vegetation data	GEMS	-
2004/PROBIO	Mapping of vegetation cover and land use for the year 2002 in 1:250,000	ETM+/Landsat-7	74.19% / 68.31%
2004/Conservação Internacional – Machado et al.	Deforestation in the Cerrado for the year 2002	MODIS	-
2004/Eva et al.	Land cover of South America from 1995 to 2000	ATSR-2/SPOT VGT/DMSP OLS	-
State	Natural remnants and characterization of reforestation with exotic species, 2000-2001 (SP)/ Mapping and inventory of native flora and reforestation, 2003 (MG)	CBERS-2/TM-ETM+/Landsat-5-7	90.8% / 89.18%
2008/PMDBBS	Quantification of deforestation in native vegetation areas in 1:50,000	TM/Landsat-5	88-92%
2008/SIAD	Changes in the vegetation cover of the remaining biome from 2002-2009	MODIS	-
2013/TerraClass Cerrado	2013 Cerrado land use and land cover	OLI/Landsat-8	80.2%
2013/Hansen et al.	Global forest gain and loss in the period 2000-2012	ETM+/Landsat-7	99.6%

(To be continued)

(Conclusion)

Initiative	Objective	Sensor	Accuracy/Kappa
2015/Beuchle et al.	Land cover changes in the Caatinga and Cerrado biomes from 1990 to 2010	TM-ETM+/Landsat-5-7	-
2015/FBDS	Production of primary data on land use and land cover, hydrography and Permanent Preservation Areas (PPAs) for the Cerrado and Atlantic Forest in 1:25,000, 2013	RapidEye	95%
2015/MapBiomas	Land use and land cover mapping of the entire national territory from 1985 onwards	TM-ETM+-OLI/Landsat-5-7-8	70-95%
2016/PRODES Cerrado	Deforestation in 1:250.000 from 2000 onwards	TM-OLI/Landsat-5-8	-
2018/DETER-B	Deforestation and changes in forest cover with a minimum area close to 1 ha, from 2018 onwards	CBERS-4/IRS	-

Source: The authors (2020).

A preliminary analysis of the initiatives presented in this study allows us to identify three mapping categories: deforestation, land use and land cover, and warnings/alerts. The initiatives that map deforestation generally use more simplified legend levels, focusing on the accuracy of the final product and the use of photointerpretation methods by experts and the vectorization of polygons based on the cumulative deforestation calculation approach. Deforestation warning and alert systems work similarly, aimed at assisting enforcement agencies and meeting the urgent demand to launch data in almost real-time. Finally, land use and land cover mapping, and warnings/alerts, invest in image processing techniques and the application of classification algorithms, and the optimization of processes and data presentation through automated approaches.

4 GUIDELINES AND FUTURE PERSPECTIVES FOR MAPPING THE CERRADO

There is a consensus in the literature that the mapping of Cerrado vegetation takes place with Remote Sensing data at the highest hierarchical level (level I), in which the biome is separated into three major classes (forest, savanna, and grassland formations) and presents a classification accuracy of more than 90% (SANO et al., 2010; NEVES et al., 2020). The challenge, however, lies in the discrimination of these classes into subcategories, which account for 11 phytophysiognomies at level II, or even 25, at level III, according to Ribeiro and Walter (2008) "The Main Phytophysiognomies of the Cerrado Biome".

Therefore, here we present some guidelines and future perspectives that aim to improve the Cerrado mapping in more detailed levels, such as levels II and III. Recent studies point to the subdivision of the Cerrado into ecoregions to aggregate homogeneous areas concerning soil and climate characteristics, geomorphology, and floristic diversity, according to the guidelines of Ribeiro and Walter (2008) (SANO et al., 2019a). These 19 subdivisions presented by the authors can be useful for mapping vegetation separately in each of the regions, decreasing spectral confusions resulting, for example, from variations in soil moisture and vegetation, phenology, sun exposure, soil formation, etc.

4.1 Remote Sensing Data

As mentioned, a major problem for mapping natural areas, especially the Cerrado biome, is about the differentiation of vegetation types. In several works (COSTA; FONSECA; KORTING, 2014; MÜLLER et al., 2015; SCHWIEDER et al., 2016), as well as in the initiatives mentioned in this study that used images of medium spatial resolution (30 m), the level of semantics (legend) of the classification differentiates forest vegetation from non-forest vegetation with a high degree of accuracy (above 80%). However, the confusion of classifying the various savanna and grassland classes remains high. In general, the most significant classification errors are found in the distinction between these features, and between other classes, such as pastures, due to the high spectral similarity. It is worth pointing out that, for the Cerrado, such confusions occur even in current mappings, resulting in the overestimation of the percentage of natural remnants (non-anthropic) when interpreting the data, as pointed out by the MMA in the PROBIO initiative and by Sano et al., (2019b) in the TerraClass Cerrado results. This occurs, especially in the Cerrado biome, since grassland phytophysiomies are natural pastures and, although they are considered natural, they are destined for anthropic use.

The use of high spatial resolution data (4 - 10 m) to discriminate these phytophysionomic classes (PINHEIRO; DURIGAN, 2009; TEIXEIRA et al., 2015; GIROLAMO NETO; FONSECA; KÖRTING, 2017; GIROLAMO NETO, 2018) presents a significant information gain for the separation of the various classes from the Cerrado. However, the volume of data produced requires efforts and new methodologies for processing this information on a biome scale. In this regard, one can highlight the FBDS mapping with the RapidEye 5 m spatial resolution scene classification, although the phytophysionomic differentiation has not occurred at more specific levels. Therefore, time series of high to moderate spatial resolution sensors are essential to separate classes that present well-defined seasonality during the year, such as grassland areas (JACON et al., 2017), and to identify and map areas with recurrent fires, such as Murundus fields. New satellite constellations such as the Planet series (3 m spatial resolution, 4 multispectral bands), which has 130 satellites (daily revisit) and SAOCOM 1A and 1B radar (7-100 m spatial resolution, L band, revisit every eight days) can help resolve the differences between classes at more detailed hierarchical levels.

Auxiliary data can be used for mapping improvements, such as vegetation indices used in most initiatives, unmixing models (PRODES), and other environmental data. Despite the vast possibility of these indices found in the literature (XUE; SU, 2017), the main indices used are NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index), using the MODIS and Landsat series sensors (FERREIRA et al., 2003, 2011; BAYMA; SANO, 2015), the former having vegetation index products ready for use. For example, the MOD13 and MYD13 products from the Terra/Aqua satellites, respectively, are preprocessed compositions (georeferenced and in surface reflectance) and cloud-free. The Landsat series images have the most extended terrestrial imaging period 1985 and at a 30 m spatial resolution, thus allowing multitemporal analysis of changes in land use and land cover in medium spatial resolution.

Regarding the spectral bands, the near-infrared, red-edge, and medium infrared are commonly used because they are spectrum bands that capture differences in canopy structure due to changes in leaf area index, water contente, and chlorophyll, in addition to the contributions of non photosynthetically active materials, mostly observed in the dry season and herbaceous vegetation (TONIOL et al., 2017). Besides the spectral variations, vegetation indices such as, beyond NDVI and EVI, the NDWI (Normalized Difference Water Index) and NDII (Normalized Difference Infrared Index) are some of the most important (HILL, 2013; TONIOL et al., 2017), as they are related to the differences in canopy structure and water content in leaves. Several well-established vegetation indices can be calculated from the multispectral bands of the Sentinel-2 for applications in savanna regions (HILL, 2013).

Differences in sensitivity of various vegetation indices are observed depending on humidity, tree cover, and phytophysiognomy. Thus, time series are necessary to fully capture spectral states and changes since grassland and savanna formations have high spectral and phenological variation (HILL, 2013). However, according to Toniol et al.; (2017), class discrimination in the Cerrado is generally made easier during the dry season, given that the rainy season requires the use of a larger number of metrics (spectral bands or vegetation indices) for the vegetation classification due to greater spectral confusion with greater homogenization between the class gradients in that period.

The difficulty of differentiating vegetation parcels is also an impediment to understanding the nature and extent of ecosystem limits since they are directly involved in the form of management and conservation of local biodiversity. These transitions, called ecotones, have high environmental complexity, species exchange between biotic communities, and hyperdynamics of vegetation by aggregating both ecosystems' characteristics. This is the case of the Cerrado-Amazonia and Cerrado-Caatinga transitions, which have large areas and are represented on official maps simply as a line for delimitation (MARQUES et al., 2020).

Abade et al. (2015) used the product MOD09Q1 (NDVI time series, MODIS sensor) in the period 2011-2013 to map native and exotic vegetation in the Cerrado-Caatinga transition zone through the SVM (Support Vector Machine) classifier and obtained an accuracy of 80.75% with six mapped classes (water, agriculture, pasture, seasonal deciduous forest, semideciduous seasonal forest, and Cerrado). The authors pointed out that phenological effects are among the greatest challenges in the study of savannas and semiarid regions. Marques et al. (2020) analyzed more than 30 years of the Cerrado-Amazon transition, using

TM/Landsat 5 images, spectral mixing techniques and automatic classification. The authors concluded that these areas recorded deforestation rates higher than forests and savannas in each biome individually. According to the authors, this limit should be redefined by a complex transition zone of approximately 250 km.

4.2 Techniques and methods

Image classification techniques and processing have evolved together with technological and computational development. Widely used algorithms such as MaxVer (Conservation International), and ISOSEG (TerraClass Cerrado), among others, are beginning to make room for Machine Learning techniques, more robust algorithms such as decision trees (MapBiomas) and the concept of data mining. Currently, the increase of new data and metrics in classification techniques has become a differentiating aspect since these data are produced on an increasingly smaller time scale. Having tools that help in the analysis of an increasing volume of data (big data) in a short period is now part of our reality, either through data mining techniques, artificial intelligence, and deep learning or through cloud computing platforms such as Google Earth Engine (SOUZA MENDES et al., 2019; NEVES et al., 2020).

Deep learning computing techniques are promising to develop a semantic segmentation of the Cerrado classes. In an experimental analysis, Neves et al.; (2020) compared the visual analysis of the WorldView-II sensor with that developed by the fully convolutional neural network (U-NET) and observed that the level of accuracy was statistically similar in both cases (81%; 90%; 88% for the grassland, savanna and forest classes, respectively). Discrepancies were observed in the transition between classes whose tree/bush densities gradually increased. These computation techniques can be expanded to perform segmentation and classification of physiognomies in more detailed hierarchical levels, using modifications in the network architecture to integrate other data sources in a synergistic way, such as Radar and optics. For example, Souza Mendes et al.; (2019) observed that Radar (ALOS/PALSAR-2, full and dual polarimetric, TanDEM-X and Sentinel-1) and optical (Sentinel-2) data information, when combined, showed a significant global accuracy gain in classification during the dry and rainy seasons (accuracy of 81.9%), although in the dry season the global accuracy showed no difference between the use of Sentinel-2 and the combined use of data. However, the authors employed the machine learning approach rather than the deep learning approach. Among the classes, Radar data (TanDEM-X and Sentinel-1, X-band and C-band, respectively) presented higher accuracy than the optical data for mapping the Gallery Forests, although these are lower for mapping the Cerradão and Dense Cerrado classes (SOUZA MENDES et al., 2019). For the secondary forest class, ALOS/PALSAR-2 dual-pol (HH+HV) radar data were also more accurate than Sentinel-2 data.

Therefore, classifiers based on decision trees or involving conditional or semantic criteria are useful to better separate certain classes according to the specific suitability of each type of data and following the geomorphological, physiological, and soil characteristics of each phytophysiognomy. For example, it is known that the Cerrado Rupestre occurs at altitudes above 900 m and areas with greater declivity and are rare outside these conditions (RIBEIRO; WALTER, 2008), so a digital elevation model can be used to refine the classification of these areas. Another example that causes much confusion is how the Veredas can be separated from radar data by their higher sensitivity to flooded and/or floodable areas (GIROLAMO NETO, 2018) or high spatial resolution sensors such as CBERS4A/WPM (8 meters spatial resolution in 4 multispectral bands, 2 meters spatial resolution in 1 panchromatic band, 31-day temporal resolution). Similarly, deep learning techniques of very high-resolution images can be used to identify the palm tree-tops in the Palmeirais (locally called Buritizais, Babaçuais, and Guerobais species) with precision in these places (WAGNER et al., 2020). Data from LiDAR such as those from GEDI (Global Ecosystem Dynamics Investigation) can be useful to separate physiognomies by the average height of the tree crowns, with the Cerradão and Cerrado restricted sense areas being restricted due to the higher average height

4.3 Generation *big data*

The abundance of data generates challenges developing routines that aim to use this volume of data at large spatial scales and with good cloud filtering quality. This challenge in data utilization can be seen, for example, in the percentage of product downloads from the Sentinel missions, where only 0.3% of all downloads in 2019 were observed in South America, indicating that users choose to download a more specific selection of data rather than a large volume (COPERNICUS, 2020). Therefore, it is essential to establish analysis methods to make the best use of the potential that high frequency of revisiting information can offer in monitoring and mapping the Cerrado, especially for operational or systematic projects.

An example is the use of platforms such as Google Earth Engine (GEE), which is based on cloud storage and facilitates access to high-performance computing resources and the processing of large geospatial data sets. Also, the platform was designed to help disseminate scientific results (GORELICK et al., 2017), having an extensive data catalog, with a wide variety of ready to use aerial and satellite images and data on environmental variables, weather and climate, land cover, topography and socioeconomics. Another possibility of GEE is the insertion of data in the platform, allowing the user to use their data to perform analysis, all this in an application programming interface (API) that supports the implementation of geospatial data analysis and processing algorithms in Javascript and Python languages (GORELICK, 2013). In this sense, methodological approaches that use different programming languages (Python, R) grow every day, allowing for the creation and sharing of ready-made analysis packages, which extends access to users with little programming experience.

Finally, considering the great extent of the Cerrado biome, it is recommended that efforts be made to form extensive field observation and data sharing networks. Information of this nature is essential for the development of more robust methodologies and algorithms, as well as for research and evaluation of new Remote Sensing technologies. In this sense, the trend is to get closer and closer to intelligent analysis, which aims at the potential for identification and discrimination of images in a similar way to photointerpretation.

In addition, the new generation of sensor systems has proven promising, with bands allocated at specific wavelength intervals (MSI/Sentinel-2), such as red-edge spectral bands that are particularly useful in differentiating vegetation, since they present greater variation in these wavelengths, and increasingly smaller pixels, which attenuates the transitions between targets and time gaps. Among the future promises are Landsat 9 (scheduled for 2021), which together with Landsat 8 will reduce the time window of the series from 16 to 8 days. Also, new possibilities are foreseen in the Hyperspectral Remote Sensing universe, with the launch of the German EnMap (Environmental Mapping and Analysis) and the American HyspIRI (Hyperspectral Infrared Imager) sensors, forecast for 2021 and 2023, respectively.

5 CONCLUSION

Significant initiatives have emerged in the mapping of Cerrado vegetation over the past 20 years, highlighting the increase in efforts to understand the dynamics of land use and land cover in the biome, especially in the last decade. Current sensors pose a challenge for the timeliness, as most initiatives use data from Landsat satellites and MODIS sensors. The latter, despite its moderate to low spatial resolution (250 m - 1 km), presents a variety of preprocessed data. Landsat, having a medium spatial resolution (30 m) and covering a period of more than 30 years, was the main data used by the initiatives presented in this study that evaluated biome vegetation’s status. Among the new generation of sensors, the use of data from the Sentinel constellation represents a promising opportunity to establish new initiatives. Likewise, the combination of high temporal resolution images with robust classification techniques is essential for advancing knowledge regarding the Cerrado's phytophysiognomic differentiation.

The diversity of classification techniques has evolved to bring us closer to intelligent analysis, which aims at the potential for identification and discrimination of images similar to photointerpretation. This tends to provide consistent support for addressing the challenges that still exist for reliable mapping of the different classes of Cerrado vegetation, overcoming the obstacles imposed by the spectral similarities of savanna, grassland, and other types of land use, such as pastures, as well as the significant effects of seasonal variations on the phenology of vegetation characteristic of the biome. Another point worth highlighting is the advance of information beyond the pixel and how this science has been directed towards a more holistic approach, involving interdisciplinary elements from various areas of knowledge.

Thus, in the effort to strategically explore new opportunities for mapping and monitoring the Cerrado biome, the following research focuses are identified: 1) Use of new and improved Remote Sensing data sets that can provide more detailed information about the structure, physiognomy, and seasonality observed in the biome; 2) Integration of sensors, such as optical and Radar, and auxiliary data, which can improve the accuracy of results; 3) Use of algorithms applied to large volumes of data and time series; 4) Development of appropriate routines for mapping, monitoring, and using high-quality image time series; 5) Development, maintenance and expansion of observational field networks and data sharing. These research lines have the potential to fill current knowledge gaps and advance the frontier of research within the Cerrado.

Precise mapping and monitoring of Cerrado vegetation, both in its physiognomies and in converted areas, is necessary to identify and designate new priority areas for conservation, and also to improve understanding of the dynamics of land use and occupation in the biome and their impacts on the carbon balance, nutrient cycling, and water resources. Therefore, it is essential to quantify the percentage of remaining Cerrado vegetation by type of phytophysiognomy, to evaluate the degree of individual threat of each, and to understand the degree of impact that each agent exerts on each phytophysiognomy. In this sense, Remote Sensing combined with the expertise of scientists who master the knowledge of this important biome is crucial in trying to contain the high rates of anthropic use of the biome.

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Authors Contribution

The first author was responsible for the administration and coordination of the project, for conceptualization, data curation, formal analysis, research, methodology, resources, software, visualization, writing at all levels (initial draft, review and editing). The second author contributed with the conceptualization, resources, visualization, writing (revision and editing). The third author helped with conceptualization, resources, data curation, research, writing at all levels. The fourth author provided resources, visualization and writing (revision and editing). The other authors participated in the writing (review and editing), the last author being responsible for supervision.

Interest Conflicts

The authors declare that there is no conflict of interest.

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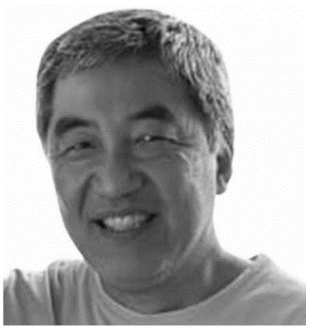

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